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Medium Access and Power Control Protocol for Wireless Sensor Networks with Directional Antennas

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Abstract - The primary contribution of this paper lies in evaluating the potential benefits of using directional antennas in wireless sensor networks to reduce node power consumption and improve fairness and throughput. The protocol helps improve throughput and reduce energy consumption by maximising spatial reuse and with a strategy to deal with overlap between antenna patterns without any additional complexity at the sensor nodes themselves. The protocol uses packets from the hub to estimate the transmission power required by nodes, to avoid excess energy usage. The protocol is verified using RiverBed Modeler. Simulation results for fairness, throughput and node transmission energy requirement are presented, showing a reduction in average transmission power by a factor of two with respect to the protocol without power control. Good fairness is demonstrated and throughput for a 4-antenna system is 2.17 times that of a single antenna system. The antenna pattern overlap, which is often assumed negligible, is shown to have a significant effect on throughput.

Keywords: Medium Access Control, Wireless Sensor Network, Directional Antenna, Power Control.

I. INTRODUCTION

Wireless sensor networks (WSNs) often use a star topology for monitoring applications, where all nodes forward their data packets towards a central sink (hub). The trade-off between power consumption, range and throughput is critical for sensor nodes, as they rely on limited stored or scavenged energy, whereas the hub is likely to have an external source of power. Directional antennas have the potential to provide increased transmission range and/or reduction in transmission power and interference by directing beams towards desired locations [1]. The use of multiple directional antennas also offers the promise of increased throughput through spatial re-use of the channel. However, the use of directional antennas introduces additional complexity and power consumption, so they are best placed on the hub node rather than the sensor nodes. In order to leverage the benefits that directional antennas bring, suitable MAC protocols need to be developed.

Despite these advantages, many existing approaches [2-8] have made a number of simplifying assumptions such as the use of idealised antenna patterns where beam overlap is ignored [7]; requiring all nodes to be equipped with a GPS, position information [5] or other additional hardware [2, 3], with the associated power usage; requiring accurate time synchronisation [8]; or having the multiple antennas operating in different frequency bands [6, 8].

The contribution of this paper lies in proposing a MAC protocol design that attempts to maximise the benefits of directional antennas, without requiring additional hardware at the sensor nodes, knowledge of node location, or external synchronization. We consider the performance of a protocol for use with directional antennas on the hub node in a star topology network. The effect of antenna pattern overlap is fully considered and shown to be a significant factor. Omnidirectional antennas are retained on the nodes to minimise the complexity of both the hardware and the MAC protocol, and to further minimise node power consumption. We evaluate the network performance in terms of energy efficiency, fairness and throughput. We base the MAC protocol in this paper on the Aloha [9] protocol as it does not require any carrier sensing or synchronisation. We introduce a power control scheme to ensure fairness for nodes at different distances from the hub. This also minimises the energy consumption and the complexity of the sensor nodes. Building on previous analysis from [10],

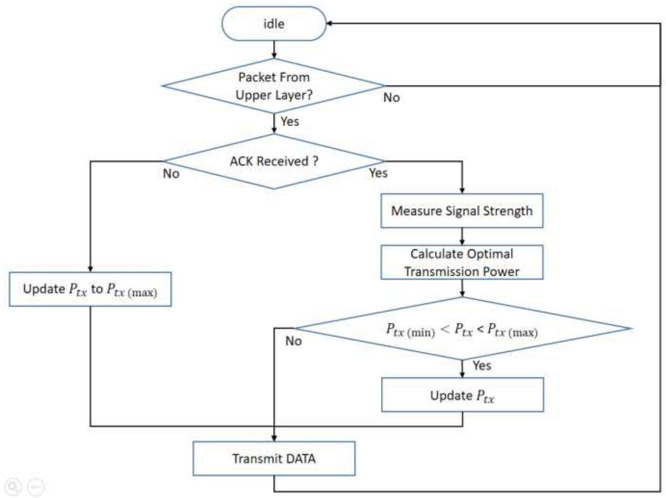


Figure 1: Node transmission power adjustment.

where we considered only a simple scenario with directional antennas, where all nodes are equidistant from the hub, in this paper we present an assessment of throughput and transmission power consumption for a realistic, random set of node locations.

The paper is organised as follows. We describe our proposed protocol in Section II. We evaluate the performance of our proposed protocol in Section III and summarise the paper in Section IV.

II. PROTOCOL AND NETWORK TOPOLOGY

We consider a planar centralised star topology based on the IEEE 802.15.4 physical layer, where n nodes gather data and transmit to a hub over a single channel. Each node is assumed to be equipped with an omni-directional antenna and nodes are free to move independently. The hub is assumed to be equipped with a number (four) of directional antennas with fixed transmission power. Each antenna serves a sector that must overlap other sectors to some extent, dependent upon the antenna patterns. Therefore, interference between sectors must be considered in any performance evaluation.

In our protocol, all data packets are transmitted on a best effort basis. The packet inter-arrival time is exponentially distributed. A node cannot send and receive at the same time. An acknowledgement (ACK) is transmitted from the hub following a successful data packet reception for the purpose of power management. The ACK might also be used to provide a reliable protocol but re-transmission of a failed packet is not currently considered.

Figure 1 shows the power management algorithm. If a node has a packet to transmit, and there has not been a previous ACK reception, the packet will be sent with maximum transmission power. Once a node transmits a data packet, it will wait for an ACK. If an ACK is received, the node records the received power of the ACK packet for the purpose of transmission power management. The node calculates the required power for a successful transmission using the received power of the ACK by assuming a reciprocal path and knowledge of the hub transmit power.

$$P_{\mathrm{T,node}} = \frac{P_{\mathrm{Thub}}}{P_{\mathrm{Rnode}}} P_{\mathrm{R,hub}} \qquad (1)$$

where $P_{\mathrm{T,node}}$ is the required node transmit power to achieve the required hub receive signal power $P_{\mathrm{R,hub}}$ if the measured node received power is P_{Rnode} and the hub transmit power (assumed known) is P_{Thub}.

If an ACK is not received after the expected timeframe, the node will set the transmission power to maximum for the next packet transmission. This method also avoids the need for nodes to monitor the channel to observe the hub signal strength, thus saving node power consumption.

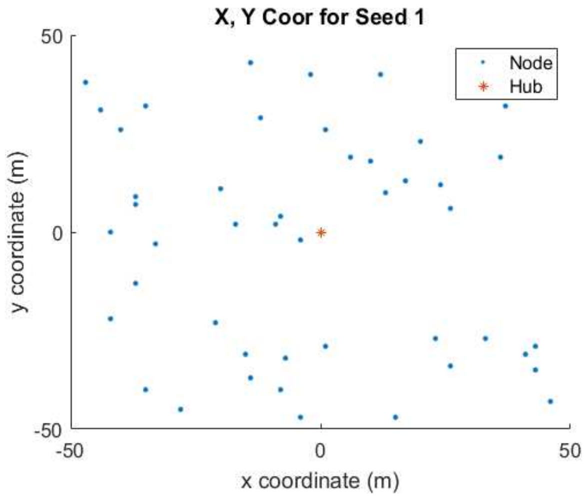
The hub protocol is a little more complex as any packet from a node may be received by more than one hub antenna. The hub must deal with duplicate packets and decide the optimum antenna with which to communicate with any node. From the point of view of the hub, the protocol corresponds to the Aloha protocol with the addition of the ACK packet used for power control and the need to track which antenna received the best packet from a node in terms of signal-to-interference-noise ratio (SNIR). The best antenna is used to return the ACK, and for any return traffic (not considered in this paper). We assume that nodes may move, as well as obstacles and sources of interference, so the optimum antenna must be allocated dynamically.

III. PERFORMANCE ANALYSIS AND DISCUSSION

A. Methodology

To evaluate the performance of the proposed protocol, simulations have been carried out using Riverbed Modeler (OPNET). The pipeline stages in Riverbed Modeler have been modified with the simulation parameters displayed in Table I.

We characterize the performance using a series of randomly generated topologies. 50 nodes are randomly deployed (using a pseudorandom number generator) in a



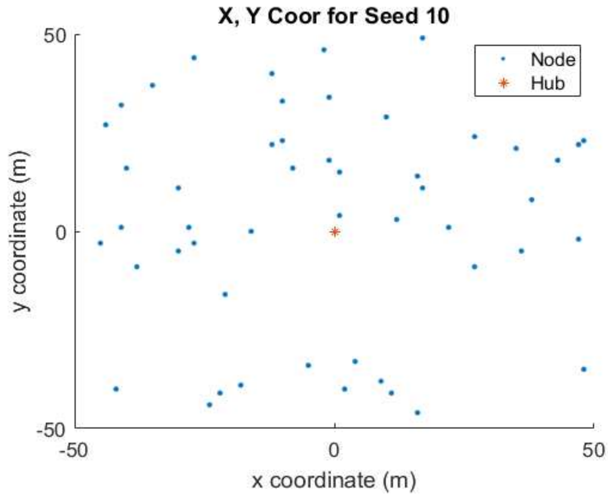


Figure 2: The map plots of two random network topologies in a 100m x 100m area with 50 sensor nodes.

100 x 100 m^2area, with the *x* and *y* coordinates uniformly distributed and independent. A single hub node is positioned at the centre of the deployment. All DATA packets are of the same length. We consider free space propagation and do not require synchronisation between nodes. Based on realistic devices, we also assume that nodes cannot start a new transmission if they are currently receiving since the hardware would prevent it. Packet reception is governed by the received signal-to-interference-noise ratio (SINR), assuming uncoded binary phase shift keying (BPSK) modulation. A look up table is used to acquire the bit error rate (BER) corresponding to the received SINR level. This BER value is used to determine whether each individual bits are received in error, based on the generation of uniformly distributed random numbers between zero and one, and comparison with the BER threshold One or more bit errors results in discarded packet. Figure 2 shows two examples of the random topologies generated.

TABLE 1: RIVERBED SIMULATION PARAMETERS

Parameters	Value
Physical layer	IEEE 802.15.4
Channel bit rate	250 Kbits/s
Network area	100m x 100m
Number of nodes	50
Maximum Transmission Power	0.01W
Average Range	35.355m
Frequency band	2.4GHz
DATA packet size	1024 bits
ACK size	8 bits

The throughput, average transmission energy per bit, and fairness of the MAC protocol were measured over 1200 packets per node and 10 different randomly generated network topologies.

B. *Node transmission energy usage*

Figure 3 illustrates the transmission energy per bit required per successful transmission. This is calculated by dividing the product of the transmission time and transmission power level by the number of successfully received bits. We can observe that the energy required per bit increases as of the offered load increases, since the increased probability of collision causes a greater number of lost packets. Therefore, as the number of attempts for a successful transmission becomes higher, the energy required per successful transmission increases. Comparing with a directional hub protocol without power control, the transmission power of the network can be reduced by a factor of two on average by employing the new protocol.

C. *Throughput*

Figure 4 shows the average throughput of our protocol using 4 directional antennas, with and without power control as a function offered load in Erlangs. It can be observed that the proposed protocol achieves a higher throughput because of the use of directional antennas and the power control scheme. The throughput of the protocol without power control is slightly lower. The reasons are that, using directional antennas introduces the possibility of spatial reuse, whilst the use of the power control

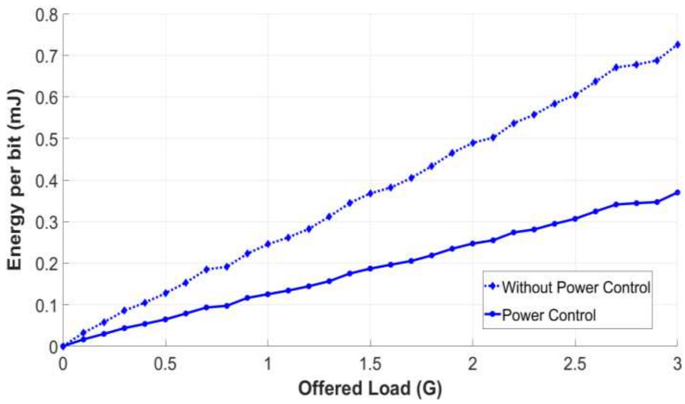


Figure 3.The reduction of required transmission energy per bit due to the proposed power control scheme.

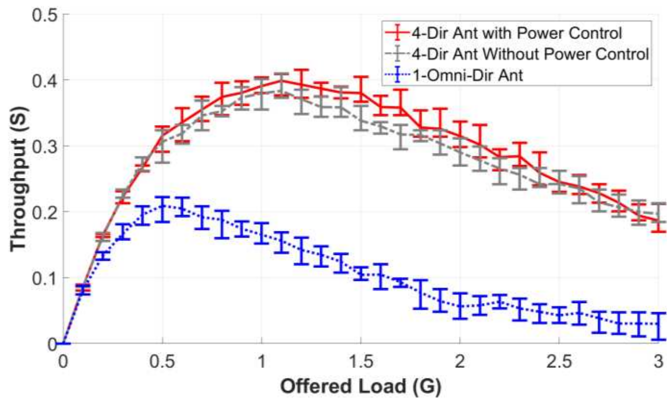


Figure 4. Simulation results illustrating the improvement in average throughput offered by the use of directional antennas and power control scheme.

scheme reduces the collisions due to antenna pattern overlap. We have also simulated Pure Aloha with a single omni-directional antenna just to show the simplest form of MAC protocol for comparison. It can be observed that the throughput can be improved significantly by using multiple directional antennas and marginally enhanced by applying a power control scheme.

Note that the use of four antennas does not give a fourfold increase in throughput as might be expected if the pattern overlap were not considered. In practice the pattern overlap, which is necessary to ensure full coverage with practical antennas, means that many nodes take part in more than one sector increasing the number of collisions and reducing throughput as shown in our previous analysis [10].

D. *Fairness*

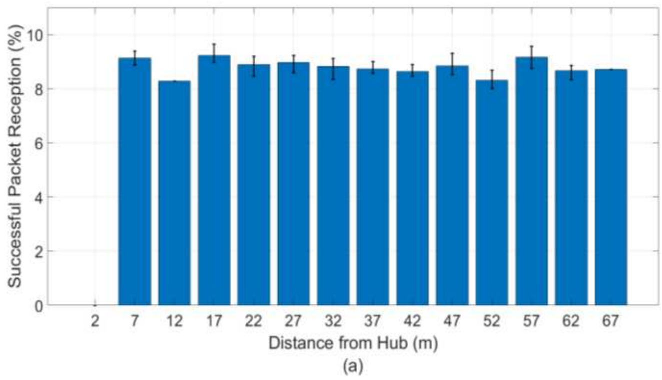
While directional antennas provide significant increase in throughput, we need to ensure that the improvement is not at the expense of fairness. Figure 5 indicates that use of the power control scheme increases the fairness of the network, as shown in figure 5 (a) with respect to the protocol without power control, shown in figure 5 (b). Increasing the distance increases the path loss in the transmission causing the SINR to decrease with distance. This result in notable unfairness to the nodes with a higher transmission distance. However, the proposed protocol provides a uniformed SINR for all nodes regardless of the propagation distance.

E. *Further Discussion*

Cost effectiveness is achieved from two aspects. The cost of the sensor nodes will not be affected despite the enhanced performance, as only the hub will be equipped with the directional antennas. The increased gain of the directional antennas at the hub can also reduce the transmission power required at the nodes, therefore resulting in a longer lifetime of the nodes and the network. In order to allow the topology to be as flexible and compatible as possible, nodes are not required to be synchronised. This can allow any nodes to be added or removed from the network at any time without disrupting the network operation. We assumed that nodes may move, so may obstacles and interference sources. The hub and individual sensor nodes are not reliant on knowledge of their own location or the position of the destination. By continuously collecting and analysing the information from the hub, sensor nodes can adjust their transmission powers simultaneously to maximise their efficiency.

IV. CONCLUSION

In this paper, a power control based MAC protocol for a star based wireless sensor network with directional antennas at a central hub is proposed. The protocol exhibits good aggregate throughput, fairness and energy efficiency performance with respect to a conventional omni-directional antenna system, whilst maintaining a simple implementation, and without the need for sensing



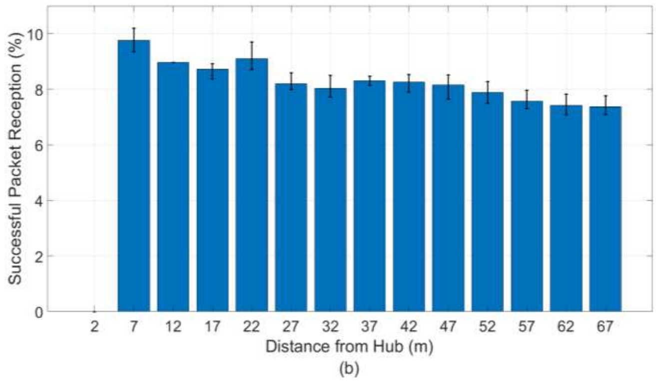


Figure 5. Successful transmission as a function of distance from the hub with (a) and without power control (b).

or synchronisation at the nodes. The scheme addresses issues of energy efficiency and fairness, by adjusting the node transmission power. At the end of each transmission, each node is able to acquire the information from the hub to formulate the required transmission power. Consequently, fairness and energy efficiency are improved. We also notice that the fairness of the network depends on the topology and the transmission power. Without a power control, nodes closer to the hub will dominate the channel. This does not affect the throughput as the number of packets received will be the same, but only a small proportion of these packets come from nodes further away from the hub. The outcome suggests that it is beneficial to employ a power control scheme in MAC with directional antennas. Given that this simplest form of its implementation already provides good performance, it is promising that future developments will offer more exciting results.

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